1. Introduction

1.1 Motivation

With the startup of NuMI in early 2005, the Fermilab program now includes two neutrino beamlines, the NuMI beam at 120 GeV from the Main Injector and the 8 GeV beam from the Booster which currently supports the MiniBooNE experiment. For the purpose of this document we refer to this beam as Booster Neutrino Beam (BNB). The goal of the Accelerator Division Proton Plan is to maximize the number of protons delivered on target (PoT) to these two neutrino beamlines in the period up to the replacement of the present Linac and Booster by the Proton Driver. This is assumed for the purposes of this document to be in 2015 or later. The plan includes a series of upgrades in the next three years to increase intensity and reliability for 10 or more years of operation.

Throughout this period the Linac, Booster and Main Injector will continue to support the production of antiprotons for Tevatron collider operation. The Main Injector will continue to play a central role in collider shot setup and will transfer antiprotons between the Accumulator and the Recycler. The proton intensity delivered for antiproton production was increased in 2005 using a technique called slip stacking (described in section 2.2 below). The Proton Plan will maintain operational compatibility with this antiproton production and collider operation.

The basis for this plan is the Proton Committee Report of October 2003 [3]. This report includes a discussion of the proton demands from the neutrino, collider and fixed-target programs, and a set of recommendations and suggestions for increasing proton supply in short, medium and long time frames. To a large extent the recommendations for the short time frame were implemented more or less immediately. These included the installation of a collimation system in the Booster to reduce radiation levels, rearrangement of the Booster doglegs, the development of slip stacking and cogging between the Booster and Main Injector (being developed under the Run II Upgrade Plan [4]), and the commissioning of longitudinal and transverse dampers in the Main Injector (also under the Run II Upgrade Plan). Upgrades to the Beam Position Monitor (BPM) and Beam Loss Monitor (BLM) systems in the Main Injector, and the BLM system in the Booster were also implemented as part of Run II.

The plan outlined here implements a specific set of upgrades for the mid- to long-term time frames, to increase the Booster repetition rate and the maximum beam intensity in the Booster and Main Injector.

1.2 Present Operational Limitations

The current bottlenecks in proton delivery are due to (1) radiation levels in Booster operation, (2) the repetition rate of the Booster, and (3) slip stacking losses in the Main Injector.

Proton losses in the Booster, leading to radiation damage, activation, and above ground radiation, have limited the total rate at which protons can be delivered. This has been the primary limitation since MiniBooNE began running in 2002. With recent improvements, including the installation of a collimation system [5] and rearrangement of the extraction chicanes (the “doglegs”) [6], a maximum of 8E16 protons per hour has now been achieved. The improvements in this plan will provide a further increase by almost an additional factor of two.

The Linac and Booster together deliver “batches” of protons at a nominal intensity of 4.5E12 protons/batch and at an instantaneous rate of 15 Hz. However, the Booster must be conditioned by two “pre-pulses” prior to a beam loaded pulse, so it is operationally advantageous to deliver protons in 15 Hz “batch trains” following each pair of pre-pulses. The maximum average repetition rate of the Booster is currently limited to 7.5 Hz by magnet cooling. The upgrades included in this plan will themselves operate at up to 15 Hz, however it is expected that power limitations in the RF system will limit Booster operation to approximately 9 Hz.

The PoT delivered to NuMI will be limited primarily by the amount of beam that can be loaded into the Main Injector, and the time it takes to accelerate that beam. The Main Injector has six usable “slots” in which to load booster batches. One slot is dedicated to antiproton production, and five to NuMI. Slip stacking will be used to load two Booster batches into one slot for antiproton production. In this plan, slip stacking will be further developed to load a total of nine batches for NuMI.

The existing Main Injector RF should be able accelerate up to roughly 5E13 protons with an acceleration rate of 205 GeV/s [7], as called for by plan. Larger batch intensities will result in increased beam loss at the limiting apertures at the injection and extraction regions of the Main Injector. These apertures were initally defined by the Lambertson septa magnets and nearby quadrupole magnets, but these quadrupoles were replaced as part of this plan. Acollimation system in the MI8 line as also installed, and a collimation within the Main Injector ring is being designed, with planned installation in 2007.

Other operations concerns focus on reliability rather than performance limitations. In particular the first stage of the Linac is now 35 years old, while the second stage was rebuilt in 1993. A reliable Linac is essential for the entire Fermilab program and must be assured for another 10 or more years. One component that has traditionally presented a worry are the 200 MHz power amplifier tubes (7835’s) in the Low Energy Linac. The Linac requires 5 of these tubes and their availability has been a reliability concern for several years, which presented a very high risk for maintaining operations. As part of this plan, Fermilab worked together with other labs and the tube company (Burle) to increase their yield and to build up strategic supply of 12 new spare tubes, which is complete as of this writing. This represents approximately a two year supply of spares in addition to the year supply of spares that we try to maintain as part of our normal purchase cycle.

1.3 Strategy

The Proton Plan is patterned after the Run II Plan. It is not a project in the traditional sense, and is not meant to include all of the activities of the departments involved. It is rather a discrete set of activities designed to bring maximize proton delivery to both the NuMI and the BNB. It is tacitly assumed that the existence of the Proton Plan will not significantly reduce the operating budgets of the Proton Source and Main Injector

Departments, and this will allow operational initiatives within these departments, some of them important to beam delivery.

Broadly speaking, Proton Plan elements fall into three categories:

1. **Increasing the proton delivery from the Proton Source**

   This has two distinct components:

   - Making improvements which will physically allow the Booster to operate at a higher average repetition rate than the 7.5 Hz that it began with. At this time, these improvements have been realized.
   - Reducing beam loss and improving beam quality in the Booster and Linac, to allow more total protons to be accelerated while still maintaining reasonable levels of activation. This represents ongoing activity.

2. **Increasing the beam intensity in the Main Injector for NuMI**

   This is principally achieved by developing multi batch operation and slip stacking, increasing the acceptance, and removing beam halo at injection. It also involves some improvements to the Main Injector RF system, which will be outlined shortly.

3. **Improving operational reliability and stability**

   This includes a number of initiatives to either reduce the actual down time of the system, or to improve the stability when it is running. It should be noted that on occasion the distinction between these elements and ordinary operational activities of the departments is rather subjective.

1.4 Proton Plan Development

The process of formulating the Proton Plan began rather informally shortly after the Proton Team Report [3], and was more formalized over the course of 2004. Discussions and meeting were held individually with representatives of the Linac, Booster, and Main Injector as well as general meetings to evaluate suggestions for appropriate projects. In general, something is included in the plan if:

- It is required to allow the acceleration of 5E13 protons per Main Injector cycle to antiproton production and NuMI.
- It is something that will significantly increase reliability or reduce beam loss and costs more than $200K.
- It is something that will significantly increase reliability or reduce beam loss and requires significant coordination between departments.

Note again that there were originall no quantitative goals with respect to the BNB, and we have tended to determine our capability for BNB proton delivery based on what can reasonably be accomplished within the budget guidance. As a specific example, we have determined that increasing the average Booster repetition rate to 9Hz is feasible within the plan but at this time it would be prohibitively expensive to increase it to 15Hz.

Initially, a number of projects were considered and/or included in the plan, but it was determined that these were really more of an operational nature, and would be better suited to remain within their respective departments. Specifically, there were a number of instrumentation upgrades, and an alignment project in the Booster.

In the following section the Work Breakdown Structure (WBS) for organizing the work on the subprojects in this plan will be described. A brief description will follow for each of the key elements of the plan, including motivation and description of the work. Section 3 will describe the methodology for estimating the cost in M&S and labor and the schedule for the work, tabulate the costs, and identify major milestones. Section 4 will describe the model for operational performance and present predictions for each phase of the upgrade plan.

1.5 Parameter Tables

The goals of the Proton Plan are summarized in parameter Tables 1.1 to 1.3. In each table, the fundamental system parameters are given, as well as parameters which affect machine performance. For the latter parameters, the initial values are given, as are the goals of the Proton Plan. The final columns show the Proton Plan elements which address that specific parameter.

Parameter	Initial Value	Goal	Relevant WBS
Fundamental Parameters			
LEL Injection Energy	.750 MeV	---	---
LEL Extraction Energy	116.5 MeV	---	---
LEL RF Frequency	201.25 MHz	---	---
HEL Injection Energy	116.5 MeV	---	---
HEL Extraction Energy	401.5 MeV	---	---
HEL RF Frequency	805 MHz		
Repetition Rate	15 Hz		
Performance Parameters			
Beam Current	30-50 mA	---	
Output Emittance	7π mm-mr	---	
Output Energy Spread	<.1%	---	
Maximum p-p shot to shot energy fluctuations (non-Gaussian)	.8 MeV	.1 MeV	1.1.4
LEL RF Amplitude Variations	1%	0.2%	“
LEL RF Phase Variations	>2º	0.5º	“
HEL RF Amplitude Variation	0.2%	---	
HEL RF Phase Variation	<2º	---	

TABLE 1.1: Initial Parameters and Proton Plan goals for the Linac

Parameter	Initial Value	Goal	Relevant WBS
Fundamental Parameters			
Injection Energy	401.5 MeV	---	---
Extraction Energy	8 GeV	---	---
Instantaneous Repetition Rate	15 Hz	---	---
Harmonic number	84	---	---
RF Frequency	37-53 MHz	---	---
Performance Parameters			
Maximum average repetition rate	7.5 Hz	9 Hz	1.2.1,1.2.2,1.2.7,1.2.13
Maximum single batch size	4.5E12	5.25E12	1.2.3,1.2.5,1.2.11,1.2.13
Maximum batch size for slip stacking	3.5E12	4.3E12	"
Longitudinal emittance per bunch (@4.3E12)	.15 eV-s	.08 eV-s	"
$\Delta p/p$ (@4.3E12)	±15 MeV	±8 MeV	"
Transverse emittance (@4.3E12)	15π mm-mr	15π mm-mr	---
Efficiency	80%	90%	1.2.2,1.2.3,1.2.11
Maximum hourly rate	6E16	1.4E16[1]	All
Average hourly rate	4E16	9E16	All

TABLE 1.2: Initial Parameters and Proton Plan goals for the Booster. Longitudinal parameters are specified for the batch sizes projected for slip stacking.

Parameter	Initial Value	Goal	Relevant WBS
Fundamental Parameters			
Injection Energy	8 GeV	---	---
Extraction Energy	120 GeV	---	---
Cycle time (mixed mode)	1.9-2.2sec	---	---
Harmonic number	588	---	---
RF Frequency	52.8-53.1 MHz	---	---
Performance Parameters			
Maximum average repetition rate	0.455 Hz	0.455 Hz	
Maximum single batch size at Injection	3.5E12	4.3E12	
Maximum beam Intensity at extraction	3.65E13 (3E13 NuMI)	4.5E13 (3.3E13 NuMI)	“
Longitudinal emittance per bunch (@4.5E13)	.4 eV-s	.4 eV-s	“
Δp/p at extraction (@4.5E13)	$\leq 8 \times 10^{-4}$ (NuMI)	$\leq 8 \times 10^{-4}$ (NuMI)	“
Transverse emittance at extraction(@4.5E12)	20π mm-mr	20π mm-mr	---
Efficiency	95%	95%	
Average hourly rate	6.0E16 (4.9E16NuMI)	7.4E16 (5.4E16 NuMI)	All

TABLE 1.3: Initial Parameters and Proton Plan goals for the Main Injector. In general, the initial parameters represent the performance of the Main Injector for slip stacked antiproton production prior to the beginning of NuMI operation.

References

3. D. Finley, *et al*, “Report to the Fermilab Director”, Oct. 2003. http://www.fnal.gov/directorate/program_planning/studies/ProtonReport.pdf
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6. J. Lackey, “New Dogleg Layout”, Booster Space Charge Meeting, May, 2003. http://www-bd.fnal.gov/pdriver/booster/meetings2/22may_layout_new.pdf

7. W.Chou, “Revised RF Power Calculations”, Booster Space Charge Meeting, Sep. 2004. I. Kourbanis “Beam Acceleration Capabilities of the Present MI RF System”. Beams Document #1927